MAT-89-02

Field Investigation of Epoxy-Coated Reinforcing Steel

Ontario

Ministry of Transportation

Research and Development Branch

Technical Report Documentation Page

Field Investigation of Epoxy-Coated Reinforcing Steel

Authors:	P. Hededahl, Ramboll & Hannemann D.G. Manning, Research and Development Branch
Number:	MAT-89-02
Date of Publication:	December 1989
Ministry Contact:	D. G. Manning, Materials Office (416) 235-4688
Abstract:	A worst case experimental design was used to investigate the effectiveness of epoxy coated reinforcement in concrete highway structures exposed to de-icing salts. Two cracked concrete barrier walls, built in 1979 which had shallow cover and were exposed to frequent applications of de-icing salts, were investigated. A similar barrier wall, also constructed in 1979 but with uncoated reinforcement, was investigated for purposes of comparison. Several test procedures were used, including determination of chloride profiles, continuity tests, half cell potential measurements, rate of corrosion and the condition of the steel and of the coating. It was recognized, and the study confirmed, that half cell potential and rate of corrosion measurements have very limited applicability on structures constructed with epoxy coated reinforcement. The epoxy coating was found to be effective in protecting the reinforcing steel in chloride contaminated concrete during the nine years of exposure, and even where the coating was damaged, there was only superficial corrosion.
Comments:	
Key Words:	barrier walls, bridges, chlorides, concrete, corrosion, corrosion potentials, epoxy coated reinforcement, rate of corrosion
Distribution:	normal distribution
Copyright Status:	Crown copyright © 1989 Ministry of Transportation

MAT-89-02

Field Investigation of Epoxy-Coated Reinforcing Steel

P. Hededahl
Visiting Research Engineer
from
Ramboll & Hannemann
Norresundby, Denmark

D.G. Manning
Principal Research Engineer
Research and Development Branch, MTO

Published by
The Research and Development Branch
Ontario Ministry of Transportation
Hon. William Wrye, Minister
P. Jacobsen, Deputy Minister

Published without prejudice as to the application of the findings. Crown copyright reserved; however, this document may be reproduced for non-commercial purposes with attribution to the Ministry.

For additional copies, contact:
The Editor, Technical Publications
Room 320, Central Building
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8

Telephone:	(416) 235-3480
Fax:	(416) 235-4872
CNCP Dialcom Electronic Mail:	23:MIN006

December 1989

Table of Contents

Introduction 1

Scope of the Investigation 2

Site Selection and Test Procedures 2
- Cover Thickness Measurements 3
- Continuity Tests 3
- Half Cell Potential Measurements (CSE) 3
- Rate of Corrosion Measurements 4
- Concrete Cores 4
- Exposure of Steel 5

Field Work 5
- N-W Ramp over Joshua Creek 5
- Eglington Avenue up Hwy 403 6
- N-W Ramp Hwy 403 over Ford Drive 6
- Continuity Test 7
- Half Cell Potential Measurements 7
- Rate of Corrosion Measurements 8
- Concrete Cores 9
- Exposure of Steel 10

Laboratory Work 10
- Chloride Content 10
- Examination of Steel and Epoxy Coating 12

Discussion 14

Concluding Remarks 17

Introduction

The Ontario Ministry of Transportation made the decision to use epoxy coated reinforcement in selected locations of highway bridges in November 1978. The change was effective immediately in bridges under design and was also implemented in bridges already under contract where it was practical and economical. The initial warrant for epoxy coated bars applied to the top mat of steel in the deck slab and sidewalk and to all the steel in the barrier wall.

In view of the relatively short time that epoxy coated reinforcement had been used in Ontario, it was decided to adopt a "worst case" experimental design rather than a random survey. A deliberate attempt was made to locate those components having the highest chloride-ion contents at the level of the reinforcing steel. Since all bridge decks are waterproofed, the investigation was limited to barrier walls and specifically to those barrier walls which had been in service the longest and in locations subject to the greatest amount of salt.

In addition to ease of access, there were two other features which made the barrier walls advantageous for this study. The first was that the concrete cover requirements in 1978 were not only much less than for other components but, because of the congestion of reinforcement, the design covers were often not achieved. Secondly, for a period of two years around 1980, slip-forming was permitted as an alternative method to forming for the construction of barrier walls. Slip-forming was banned after major deficiencies, notably shrinkage cracks, voids caused by lack of compaction, and extensive cracking caused by the

horizontal bars in the top of the wall, were discovered. These deficiencies facilitated the access of chloride ions to the embedded steel and afforded the opportunity to examine the performance of coated reinforcement in cracked concrete.

Scope of the Investigation

Sections of two reinforced concrete barrier walls on highway bridges constructed in the late 1970's were subjected to a thorough study to assess the effectiveness of the epoxy coating on the reinforcing steel embedded in concrete. The two locations are believed to represent some of the most corrosive environments for the embedded steel in any highway structure constructed with epoxy coated reinforcement in Ontario. For comparison, a section of a barrier wall with uncoated reinforcement, which was similar in all aspects of concern to the two sections constructed with epoxy coated reinforcement, was also investigated.

Site Selection and Test Procedures

A total of 14 structures, constructed in the period late 1978 to 1982, was initially included in the study which was conducted in the summer of 1988. Each structure was visually inspected, cracks and rust stains were recorded, the cover thickness was measured in randomly chosen areas of the barrier wall, and finally, based on these observations and measurements, a location on the inside face of the wall was selected and a core taken. The core, having a diameter of 50 mm and a length of approximately 125-150 mm, was analyzed in a laboratory to determine the chloride profile in the wall in general, and the chloride content at the level of the steel in particular.

Based on the results of the preliminary inspection and tests, the number of structures originally chosen for the study was reduced to include only the two structures where the embedded epoxy coated steel was considered subjected to the most corrosive conditions. Subsequently, several approaches were applied on these two structures to address the main objective of the study, an assessment of the effectiveness of epoxy coating of reinforcement. The test procedures included the following:

Cover Thickness Measurements - Pachometer measurements were taken on every second vertical bar on the inside face of the barrier wall to locate the area, approximately 1.0 to 1.5 m^2, with the least cover thickness and the position of the rebars within this area.

Continuity Tests - Since the epoxy resin is not electrically conductive, two epoxy coated rebars, crossing or overlapping each other, are expected to be electrically discontinuous. Thus, a continuity test on two such bars gives an indication, however poor, of the condition and adequacy of the coating on the two rebars tested. All crossing and overlapping rebars within the selected area were tested for electrical continuity.

Half Cell Potential Measurements (CSE) - Half cell potentials were measured extensively throughout the selected area. The potentials were measured by attaching the voltmeter to each rebar in turn, in order to ensure a proper ground connection because of the lack of electrical continuity between the coated rebars. It was recognized that the use of half cell potential measurements on epoxy coated reinforcement in concrete is beyond the scope of ASTM C 876, and

that the results would have to be appraised very carefully and critically. It was believed, however, that the measurements might provide useful information on corrosion activity of the steel.

Rate of Corrosion Measurements - The rate of corrosion measurements were performed in one location on each rebar, generally the location that was expected to be the most active based on the continuity tests and half cell potential measurements. The test is performed by applying small increments of external current to the corroding steel and measuring the corresponding potential shift from the corrosion potential of the steel at each step. Since half cell potential measurements constitute a very significant part of the test, precautions, similar to those previously described for the potential measurements, were observed when performing the test and analyzing the output.

Concrete Cores - Concrete cores with a diameter of 100 mm were drilled full depth through the wall at locations where the previous tests had indicated the highest corrosion activity, where the harshest conditions for the embedded steel were expected with respect to chloride level and exposure time, and where the condition of the epoxy coating was expected to be the poorest. This was principally near the top of the wall where the hook on the stirrup not only had a small radius but often had to be adjusted after fixing because the specified wall thickness was insufficient to accommodate the hook and provide the specified cover. The cores were analyzed in the laboratory to determine the chloride profile through the wall and the chloride content at the level of the reinforcing bars embedded in the cores. Furthermore, these rebars were subjected to a close examination to determine the condition of the coating as well as that of the steel.

Exposure of Steel - Finally, at the test site expected to form the most corrosive environment, the rebars were exposed by mechanically removing the concrete cover. The exposed rebars were visually inspected to determine the condition of the epoxy coating and of the steel and to compare these observations to the results of the half cell potential readings and the rate of corrosion measurement.

For comparison, a similar investigation was performed on a section of a barrier wall with uncoated rebars and which was similar in all aspects of concern, especially in terms of age, concrete quality, cover thickness, and service conditions, to the barrier walls with epoxy coated reinforcement.

Field Work

Based on the outcome of the preliminary study, the following two bridges with epoxy coated reinforcement were selected for further investigation:

Site No. 100140B, N-W ramp over Joshua Creek

Site No. 240319, Eglinton Avenue UP, Hwy 403.

Both were completed and placed in service in 1979. The bridge with uncoated bars selected for the comparison study was Site No. 100285, N-W ramp Hwy 403 over Ford Drive was also completed and placed in service in 1979, and was constructed in the same contract as the bridge at Site 100140B. The contract was under construction when the decision to use coated reinforcement was made, such that those bridges constructed first had uncoated reinforcement, while the bridges constructed later in the contract contained coated bars.

N-W Ramp over Joshua Creek

The preliminary inspection of the barrier walls on this structure showed a few major vertical cracks and scattered pattern cracking, but only minor evidence of

premature deterioration of the concrete. However, at one location, there was a wide crack extending the full depth through the wall from top to bottom at the position of a vertical rebar, giving free access for chlorides to the rebar. Furthermore, the preliminary test revealed that the chloride content at the level of the steel generally was well beyond the threshold value for corrosion. A very corrosive environment was therefore expected at the rebar intercepted by the crack.

Eglinton Avenue UP Hwy 403

Like the majority of structures included in the preliminary study, the barrier walls on this structure appeared sound and, except for some vertical cracks and pattern cracking, without evidence of serious premature deterioration. There was no visual evidence of ongoing corrosion activity. However, the preliminary study revealed that the reinforcing steel in this structure was exposed to the highest level of chlorides of any of the structures included in the study, and well in excess of the threshold content expected to cause corrosion activity on uncoated rebars.

N-W Ramp Hwy 403 over Ford Drive

The preliminary inspection of the barrier walls on this structure showed a more advanced level of deterioration compared to the structures with epoxy coated reinforcement. The concrete surface appeared with vertical cracks and pattern cracking very similar to what was found on the barrier walls with epoxy coated rebars. However, these deficiencies were accompanied by extensive corrosion activity causing severe rust staining throughout the concrete surface. The chloride content in the concrete at the level of the rebars was well beyond the threshold value, but below what was found in the Eglinton Avenue Bridge.

Continuity Test

The continuity test on the Joshua Creek Bridge showed resistances between the rebars ranging from 420 ohms to 6000 ohms, implying that all rebars in the test area were electrically disconnected.

The test on the Eglinton Avenue Bridge revealed electrical continuity between the horizontal bars and two of the vertical bars, bars D and O, located in the test area (see Figure 2), indicating inadequate coating on these rebars. Each of the remaining vertical rebars were electrically isolated.

All bars located in the test area on the Ford Drive Bridge were electrically connected, as expected.

Half Cell Potential Measurements

The results of the half cell potential measurements are shown in Figures 1, 2, and 3.

For the Joshua Creek Bridge, as shown in Figure 1, the vast majority of the readings were more negative than -200 mV which, according to ASTM C 876, indicates possible corrosion activity on uncoated rebars, and a significant number of the readings were more negative than -350 mV, indicating a 90% probability of corrosion on black steel.

The readings on the Eglinton Avenue Bridge were generally less negative than the readings from the Joshua Creek Bridge, but again, the vast majority of the readings were more negative than -200 mV. There was no pronounced difference between the readings obtained on the electrically connected rebars and those

obtained on the remaining bars. However, there was a tendency for the readings on the continuous bars to be more consistent, ranging from -220 mV to -368 mV, compared to the readings on the electrically isolated bars which ranged between -122 mV and -370 mV.

In accordance with the visual observations, the half cell potential measurements (see Figure 3) on the Ford Drive Bridge indicated very extensive corrosion activity on the embedded rebars, when the ASTM C 876 criteria for uncoated steel were applied.

Rate of Corrosion Measurements

Figures 4, 5, and 6 show the results of the rate of corrosion tests at the respective bridges.

As mentioned previously, each rebar was tested separately by applying small increments of external current, ΔIapp, to the steel and measuring the corresponding potential shift, ΔE, from the static potential of the steel. The test procedure is usually referred to as the three electrode linear polarization method (3 LP-method). The theoretical basis of this method is the Stern-Geary equation:

$$Icorr = \frac{\beta c \beta a}{2.3\,(\beta c+\beta a)} \cdot \frac{\Delta Iapp}{\Delta E}$$

where βa and βc are the anodic and cathodic Tafel slopes, respectively, expressing a linear dependency between the corrosion current Icorr and the ratio ΔIapp for small changes in potential. Consequently, the slope of the plots in Figures 4, 5, and 6, the polarization resistance ΔE , is inversely proportional to the corrosion current, i.e. the Iapp steeper the slope, the less corrosion

activity. Although all rebars were tested, only the results from approximately 15% of the epoxy coated rebars are included in Figures 4 and 5. On the remaining coated rebars, the potential response to the applied current was small and erratic so that the polarization resistance could not be calculated. Figure 6 gives a representative sample of the results obtained on the uncoated rebars. In accordance with the visual observations, a significantly higher corrosion activity, approximately a factor of 3, was found on the uncoated rebars compared to the epoxy coated rebars, assuming the Tafel slopes are identical in the two situation. This assumption is however, very likely erroneous, as will be discussed later.

Concrete Cores

The cores for the laboratory testing were drilled at the locations shown in Figures 1, 2, and 3.

On the Joshua Creek Bridge, the cores were taken at two locations, through the vertical crack previously described, and extending full depth from the top to the bottom of the wall. Staining in the vicinity of the crack on the back face of the wall indicated that water had been leaching from the crack.

On the Eglinton Avenue Bridge, the samples were taken at the electrically connected bars D and H as indicated on Figure 2. Core EA1 included, besides the uppermost part of bar D, the hairpin bend of the stirrup in the top of the wall. Core EA2 included the crossing bars D and H.

The two samples from the Ford Drive Bridge included a vertical and a horizontal bar respectively. The samples were taken from locations on the wall which were comparable to the sample locations on the barrier walls with epoxy coated reinforcement.

Exposure of Steel

After drilling out the cores at the positions indicated on Figure 2, the reinforcement in the test area on the Eglinton Avenue Bridge was exposed to a thorough examination of the embedded steel and the epoxy coating. The overall impression was that both performed well. The only evidence of corrosion activity was found on a hairpin stirrup in the top of the wall at the continuous bar D. This corrosion activity, however, was insignificant and confined to a small area of steel without epoxy coating. It appeared that the coating had been damaged during installation. There was no evidence on any of the exposed rebars that the coating had been patched prior to the placement of the concrete.

Laboratory Work

Chloride Content

The results of the chloride content analyses are given in Figures 7, 8, and 9 showing the profiles of the acid-soluble chlorides after subtracting the background chloride content in the concrete. The background chloride contents for the Joshua Creek, Eglinton Avenue, and Ford Drive bridges were 0.05, 0.01, and 0.06 percent chloride ion by mass of concrete respectively. The table below summarizes the chloride content at the level of the steel in the respective locations.

Location	Acid-Soluble Chloride Content % Cl^- by Mass of Concrete
Joshua Creek Bar C in crack	approx. 0.03
Eglinton Avenue Bar D	0.12 to 0.16
Ford Drive Verticals	0.06 to 0.10

Assuming a chloride corrosion threshold of 0.20% by mass of cement, the threshold is 0.03% Cl^- by mass of concrete in all three instances. This assumption is probably conservative in this case because the background chloride content has been subtracted.

The analyses of the cores from the Joshua Creek Bridge were specifically directed towards determining the chloride content on the crack surface. The cores were therefore broken along the crack (see Figure 10) and samples of concrete were milled from the crack surface to a depth of 2 to 4 mm and a width of approximately 10 mm across the diameter of the core. For comparison, the result of the preliminary test (measured by sampling pulverized discs cut from the cores) is included in Figure 7, giving the chloride profile in an uncracked area of the same wall panel. Note that the chloride profile along the crack, contrary to what was expected, is significantly below the chloride profile in the uncracked area and that the chloride content on the crack surface at the level of the steel is approximately at the threshold value. This is probably due to seasonal fluctuations of the chloride content. The concrete cores were collected

in August. The nature of the crack, the width, depth, and extent, probably allows that chlorides, which penetrate the crack during the winter, to be flushed by rain during the rest of the year.

The chloride profiles of the cores from the Eglinton Avenue Bridge and from the Ford Drive Bridge were determined by slicing the cores using conventional Ministry procedure (i.e. slicing the cores into discs, pulverizing the whole disc, and sampling the powdered concrete). These profiles all display decreasing chloride content in the outermost part of the wall compared to a maximum at approximately 10 mm depth in the wall. The most likely explanation is that chloride contents exhibit the same seasonal dependency as recognized at the crack on the Joshua Creek Bridge.

Core EA1 from the Eglinton Avenue Bridge was taken from the top of the wall and has therefore been exposed to chloride ingress from both the top and the face of the wall, which presumably explains the more inconsistent readings and the higher chloride content compared to the remaining two cores, as shown in Figure 8.

Examination of Steel and Epoxy Coating

The samples of rebars from the Joshua Creek Bridge showed no evidence of any corrosion activity. The state of the epoxy coating on the samples was very good and without any noticeable deficiency. Generally, the measured thickness of the epoxy coating was within the specification requirements of 0.18 +0.05 mm. However, a few readings were below the required minimum thickness of the coating. There was no evidence of debonding between the steel and the coating.

Minor surface corrosion activity was found on a small area of steel without coating on the hook portion of the vertical bars from the Eglinton Avenue Bridge, but, with the exception of this case, there was no evidence of corrosion on any of the bars in the cores. The adjacent section of the same stirrup also showed similar superficial corrosion activity was found when all the reinforcement in the test area was exposed. There was no pitting nor evidence of corrosion activity under the coating adjacent to the damaged area.

Evidence of isolated examples of poor bond between the epoxy and the ribs on the bar was found on all of the bars by prying the coating with a knife. The coating between the ribs could not be removed by scoring a cross and prying with a knife. There was also evidence of damage to the coating on some of the ribs which appeared to be the result of bar-to-bar abrasion during handling or transportation. Extensive lateral hairline cracking and damage to the coating on the ribs were found on the upper part of the hairpin bend from the stirrup in the top of the wall, Core EA1, whereas the coating on the underside of the bend had a few hairline longitudinal cracks and occasionally areas of debonding. The radius of the bend was measured to be approximately 8 times the bar diameter, which was also the minimum permitted by the specification.

The electrical continuity, recorded in the continuity test, between the crossing bars D and H was apparently caused by damage found in the coating in the area of contact on both rebars involved, Core EA2. As indicated above, however, in neither of these two cases was noticeable corrosion activity observed. The average thickness of the coating was within the requirements of the specification.

Discussion

The chloride profile through the barrier wall and the chloride content in the concrete at the level of the reinforcement in the test area on the Eglinton Avenue Bridge implies that the epoxy coated reinforcement at this location had been exposed to a corrosive environment for a number of years. Compared to these results, the chloride analyses of the concrete from the test area on the Ford Drive Bridge revealed considerably less contamination, indicating that the uncoated reinforcement at this location had been exposed to a corrosive environment for a shorter period of time. Despite the results of the chloride analyses of the cracked cores from the test area on the Joshua Creek Bridge, it is likely that the rebar intercepted by the crack is in a similar corrosive environment as the rebars in the test area on the Eglinton Avenue Bridge for a significant part of a year.

However, as described previously, apart from insignificant and localized surface corrosion on one severely damaged coated rebar on the Eglinton Avenue Bridge, there was no evidence of corrosion activity on the reinforcement in either of the two barrier walls constructed with epoxy coated reinforcement, whereas extensive and severe corrosion activity was found on the barrier wall with ordinary uncoated reinforcement on the Ford Drive Bridge.

The absence of, or the superficial corrosion activity observed on the areas of steel exposed by damage in the coating on the epoxy coated rebars can be explained by factors affecting microcell and macrocell corrosion. The damage in the coating was very localized, exposing only a small area of steel and therefore only a small cathodic area is available to sustain a microcell action.

Furthermore, because the area was small, it is unlikely that major potential differences existed on the steel surface within the exposed area, and the microcell corrosion activity would tend to be negligible. With respect to macrocell corrosion, the exposed steel would tend to be anodic, but, because of the coating on the adjacent steel and a lack of an electrical connection to uncoated steel, there was no cathodic area to support macrocell activity. The generally good bond between the steel and the epoxy coating probably also played a beneficial role in arresting corrosion on exposed areas of steel by preventing the access of corrosion and oxygen under the coating adjacent to the damaged area. On the majority of the coated rebars, the epoxy coating appeared to meet the requirements of the specification in effect at the time of construction. All these rebars performed satisfactorily.

While the half cell potential measurements and the rate of corrosion measurements on the barrier wall on the Ford Drive Bridge together with the visual observations, predicted extensive corrosion activity on the embedded uncoated rebars, the fact that similar potential values were recorded on barrier walls with epoxy coated reinforcement seemed inconsistent.

Half cell potentials, which according to ASTM C876 would indicate extensive corrosion activity on uncoated reinforcement, were measured frequently on both structures with epoxy coated reinforcement, yet, in the case of the Joshua Creek Bridge, without any evidence of corrosion activity on the rebar.

Different corrosion situations can be visualized by plotting, on the same graph, the log of the absolute current (I) versus potential (E) curves which would be obtained by polarizing each half cell with an auxiliary counter electrode in the

absence of the other half cell, as shown in Figure 11. The rest potential or open circuit potential of the corroding sample will be that at which the two curves intercept. At this point, no net, external current flows, and the absolute value of the current at the intercept is equal to the corrosion current ($Icorr_1$). $Ecorr_1$, measured by a reference cell, is the mixed potential of the anode and cathode. If the cathodic process is slower (the one with the large polarization), the corrosion rate is considered to be cathodically controlled which is the case illustrated in Figure 11 and the usual case for steel in concrete. The most probable explanation of the high potentials of the coated reinforcement without corrosion is that the coating restricts the access of oxygen to the steel surface. This slows the cathodic reaction with the result that the cathodic polarization increases and the slope of the cathodic curve approaches infinity. The mixed potential measured by the half cell ($Ecorr_2$) then approaches the anodic potential of the corrosion cell which is likely present at a holiday or break in the epoxy coating. At the same time as $Ecorr_2$ becomes more negative; $Icorr_2$ is reduced, which explains why small corrosion currents can be associated with highly negative potential readings.

The overall conclusion, based on the outcome of the measurements and the discussion above is that the applicability of half cell potential measurements and rate of corrosion measurements using the three electrode linear polarization method to assess corrosion activity on epoxy coated reinforcement is very limited. However, some information can be deduced primarily from the rate of corrosion measurement. By comparing the plots in Figures 4 and 5, illustrating the outcome of the rate of corrosion measurements on the epoxy coated reinforcement, it is seen that the reading indicating the highest corrosion activity is from the rebar actually found to corrode, the continuous bar D from

the Eglinton Avenue Bridge. Furthermore, in accordance with the visual observations, the plots in Figures 4 and 5 imply very low corrosion activities on the tested rebars, having taken the uncertainty on the proper value of ßa into consideration.

Concluding Remarks

The effectiveness of fusion-bonded epoxy coatings in preventing chloride-induced corrosion of reinforcement in concrete highway structures has been questioned recently. However, in the present study, little evidence was found supporting that concern. Both rebars with epoxy coating meeting the specified requirements and rebars with damaged coating performed satisfactorily with only superficial corrosion activity observed on the latter. The comparison of the performance of barrier walls constructed with epoxy coated reinforcement to the performance of barrier walls constructed with uncoated reinforcement subjected to similar exposure conditions indicated that the epoxy coating, during the first nine years in service, had reduced the corrosion activity on the reinforcing steel substantially. Although the initial indications are promising, the effectiveness of epoxy coating on reinforcing steel over the life of the structure is still uncertain. Furthermore, the study indicated that even a badly damaged bar provides significant protection of the steel, but this must not be interpreted as a reason to relax existing requirements. It is of the utmost importance that the current specification requirements be enforced to ensure satisfactory performance.

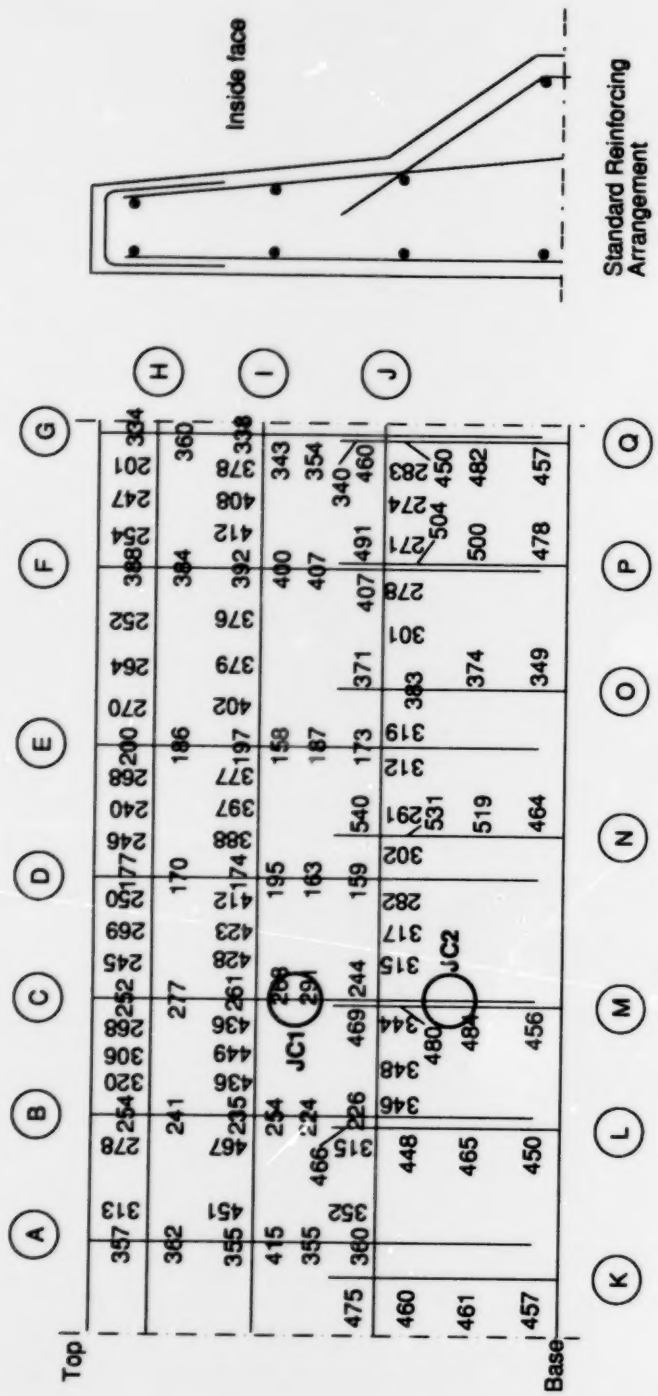


Figure 1/ Joshua Creek Bridge: Half Cell Potential Data (CSE/ mV) - negative sign omitted

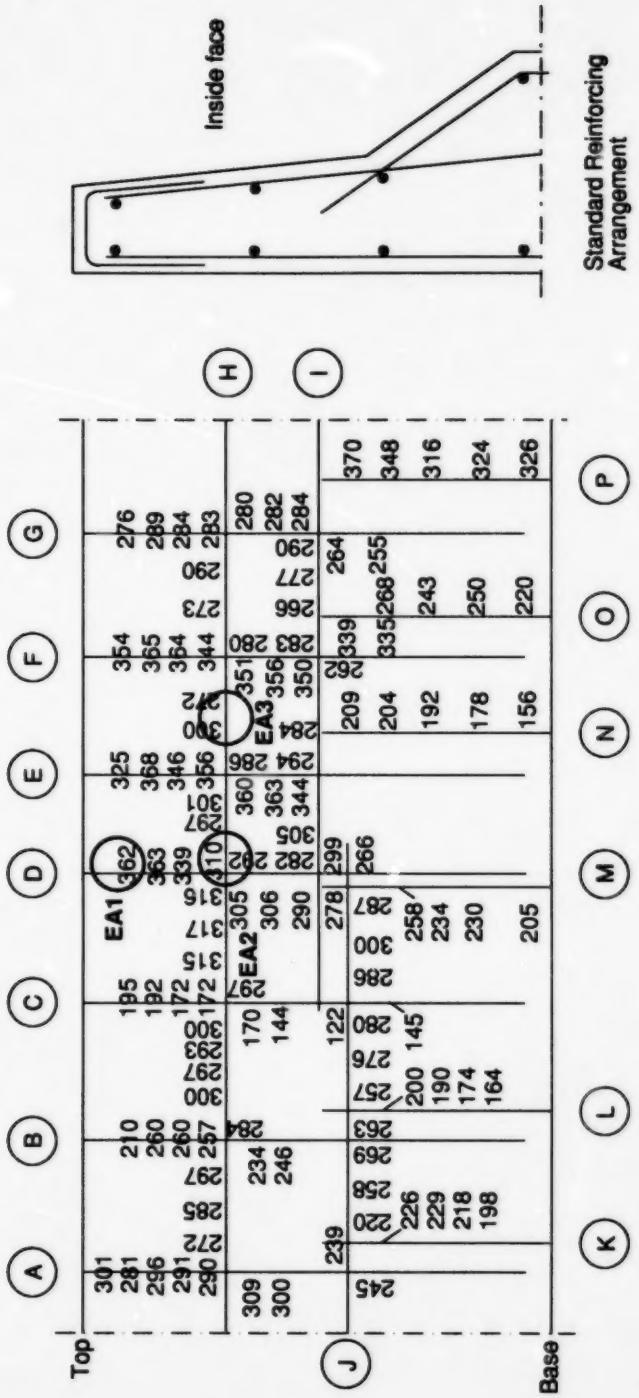


Figure 2/ Eglington Avenue Bridge: Half Cell Potential Data (CSE/ mV) - negative sign omitted

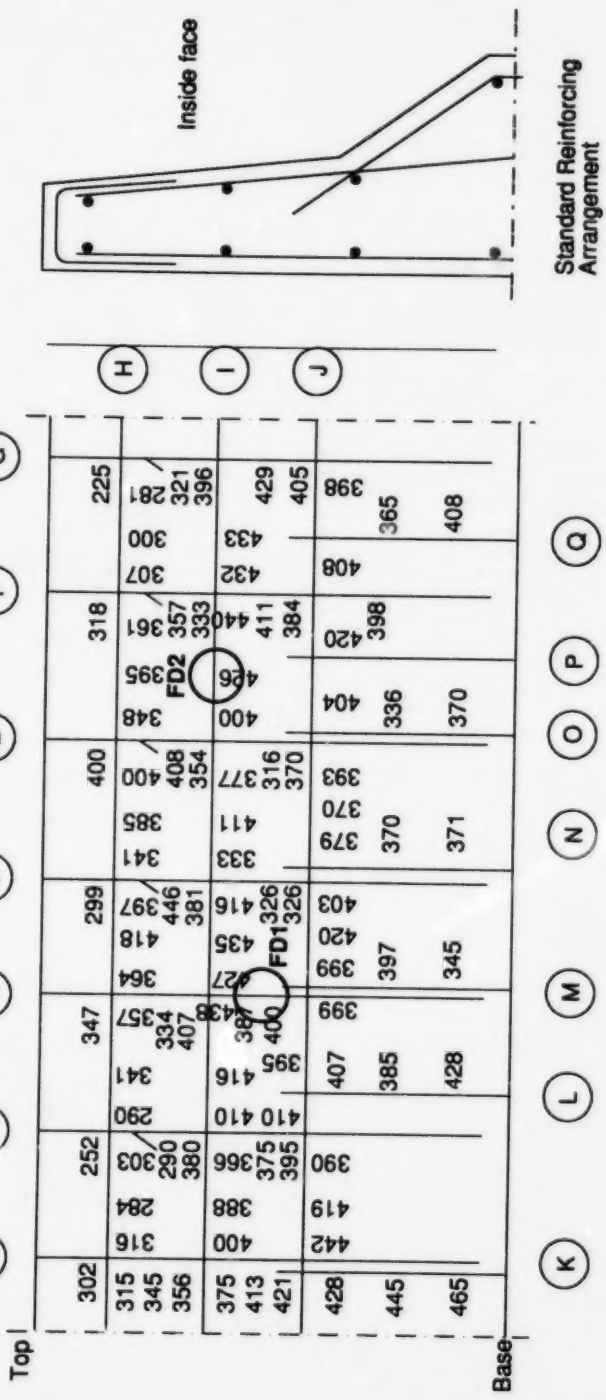
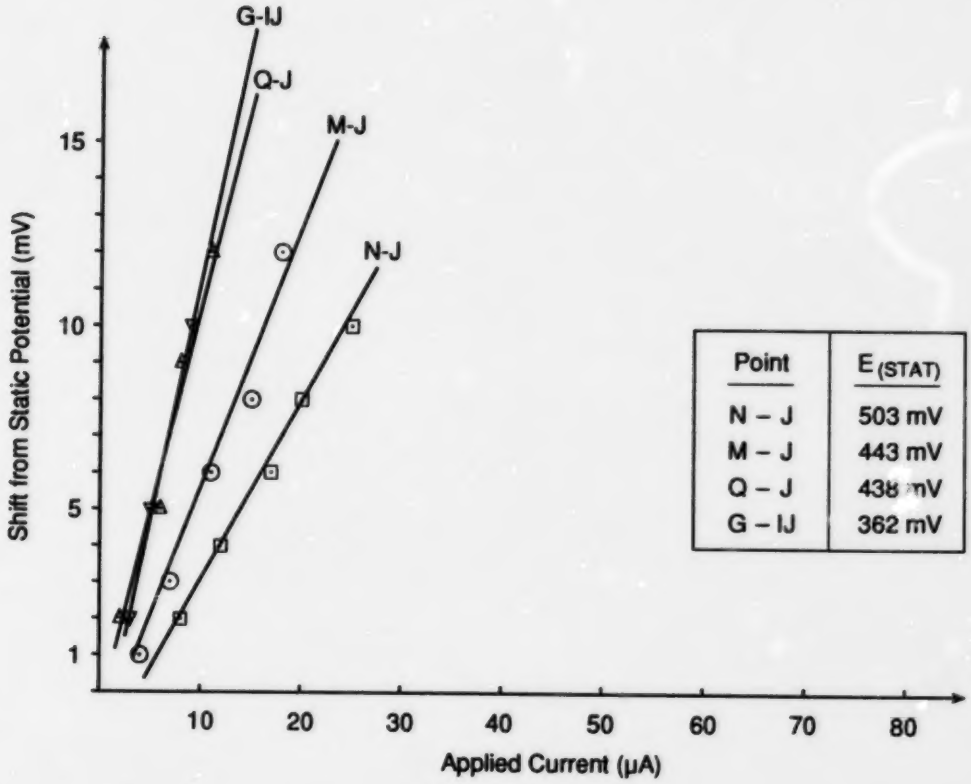
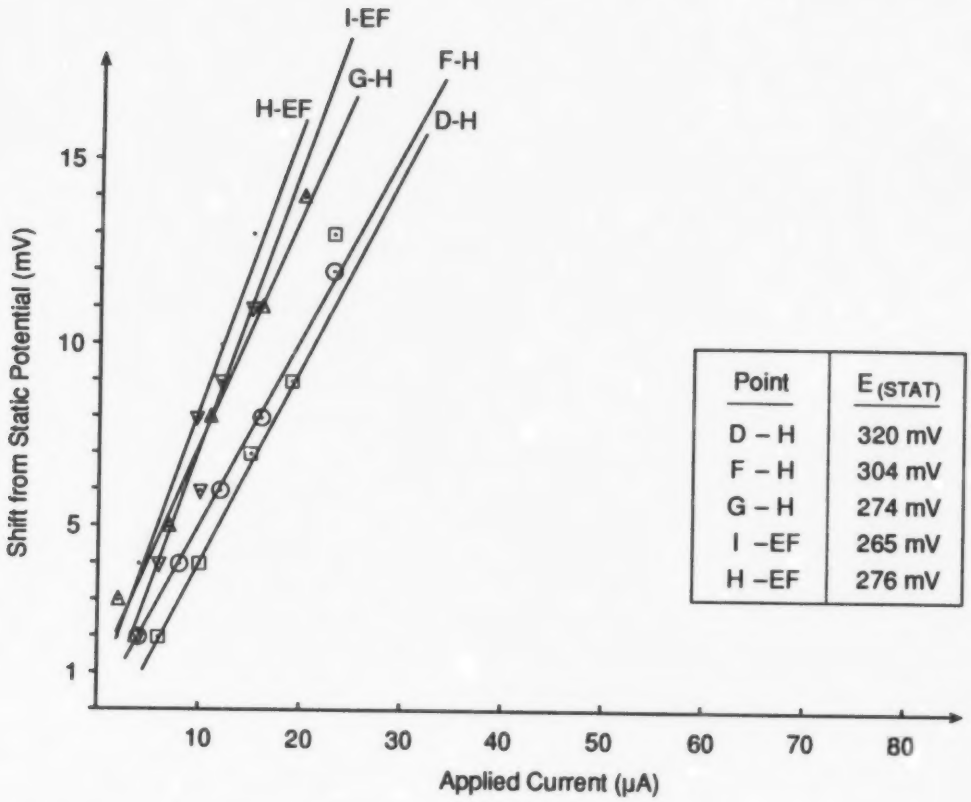


Figure 3/ Ford Drive Bridge: Half Cell Potential Data (CSE/ mV) - negative sign omitted



Point	$E_{(STAT)}$
N – J	503 mV
M – J	443 mV
Q – J	438 mV
G – IJ	362 mV

Figure 4/ Joshua Creek Bridge: Three Electrode Linear Polarization Data



Point	$E_{(STAT)}$
D – H	320 mV
F – H	304 mV
G – H	274 mV
I –EF	265 mV
H –EF	276 mV

Figure 5/ Eglinton Avenue Bridge: Three Electrode Linear Polarization Data

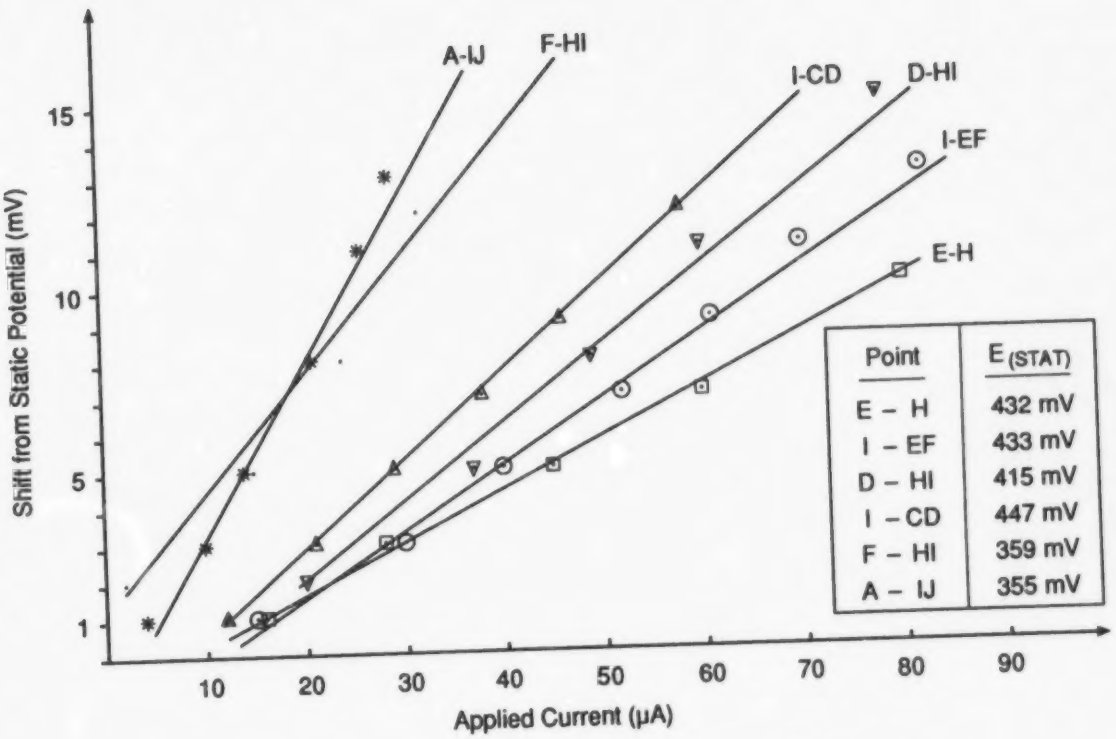


Figure 6/ Ford Drive Bridge: Three Electrode Linear Polarization Data

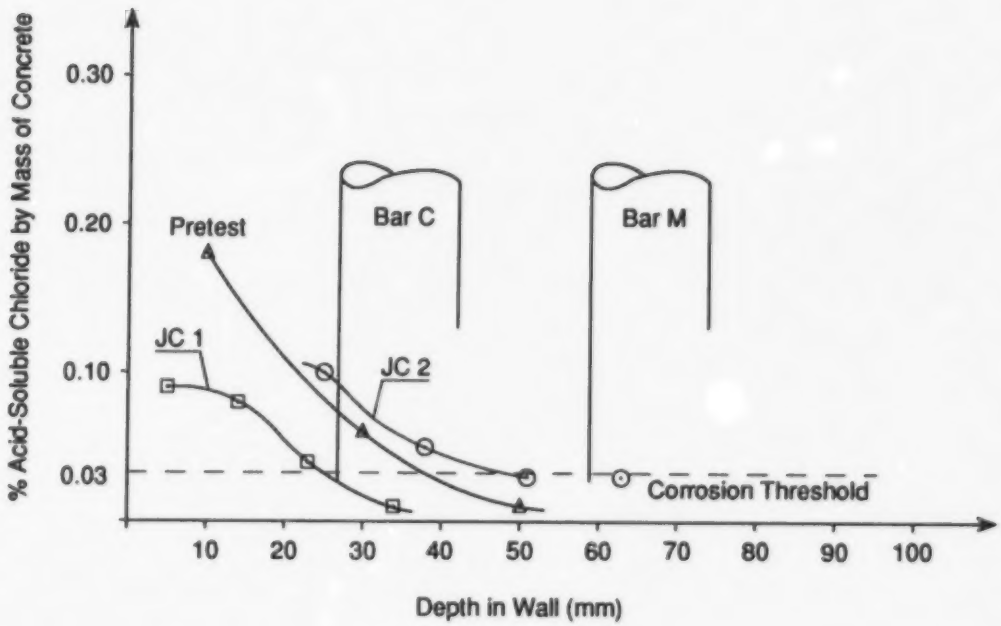


Figure 7/ Joshua Creek Bridge: Chloride Profiles

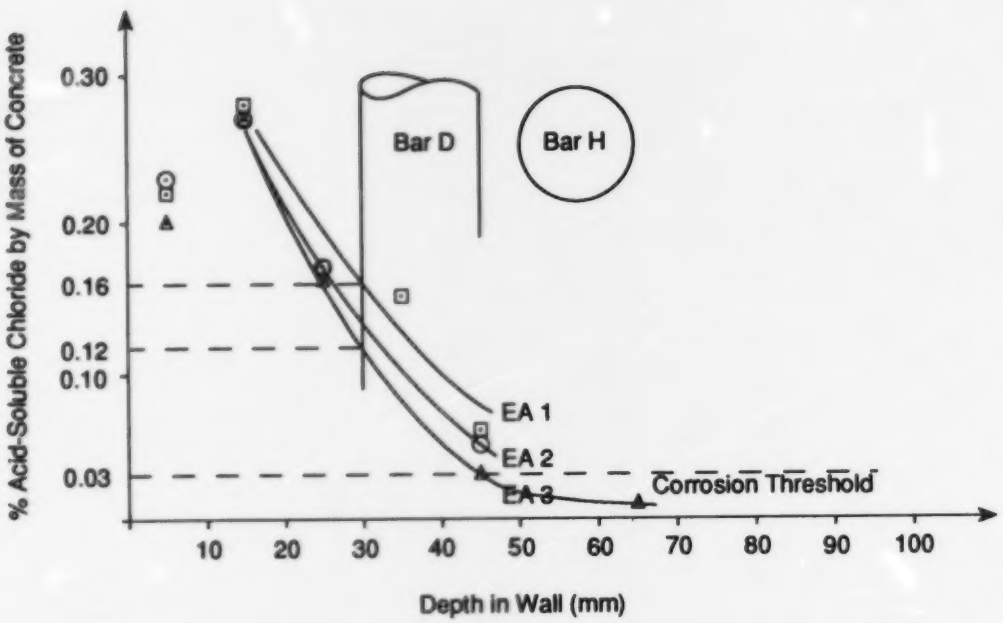


Figure 8/ Eglinton Avenue Bridge: Chloride Profiles

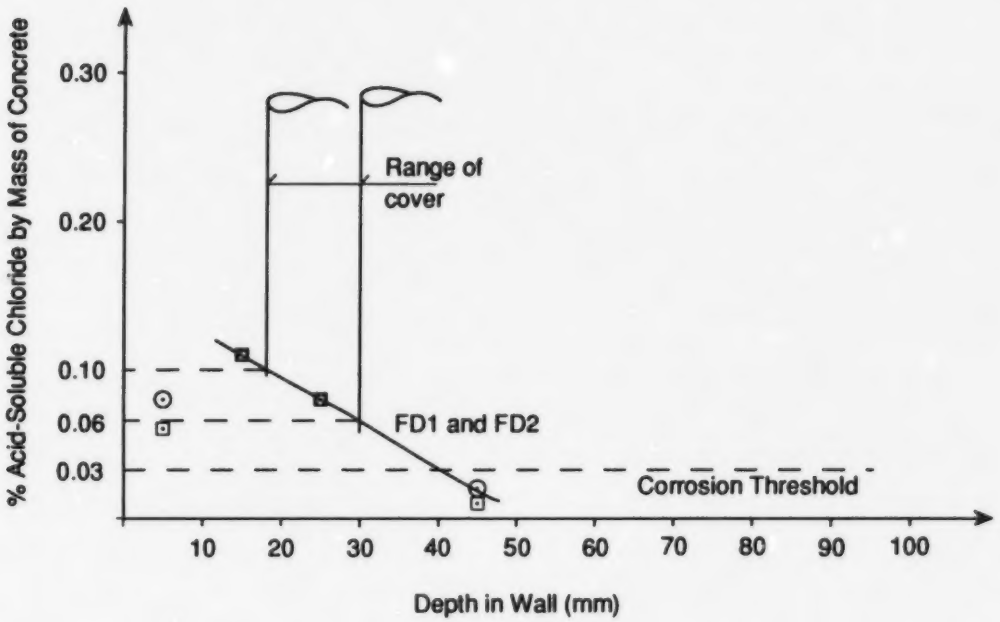


Figure 9/ Ford Drive Bridge: Chloride Profiles

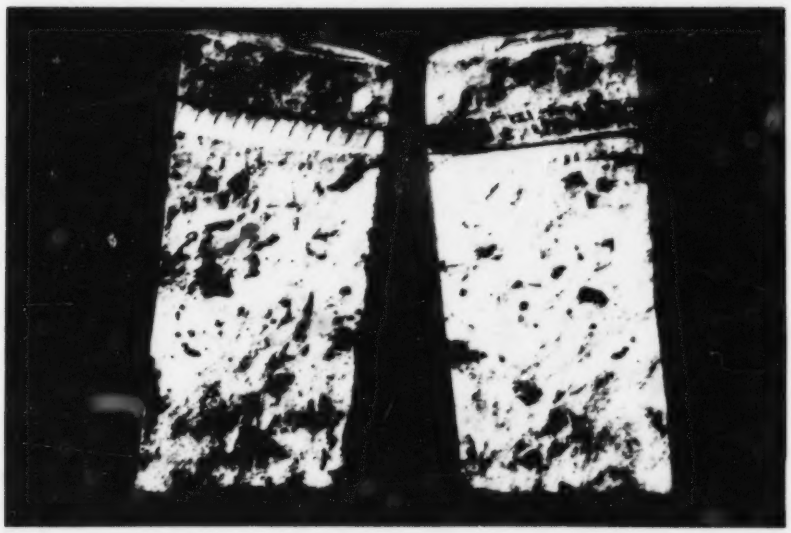


Figure 10/ Cracked core JC1 from Joshua Creek Bridge

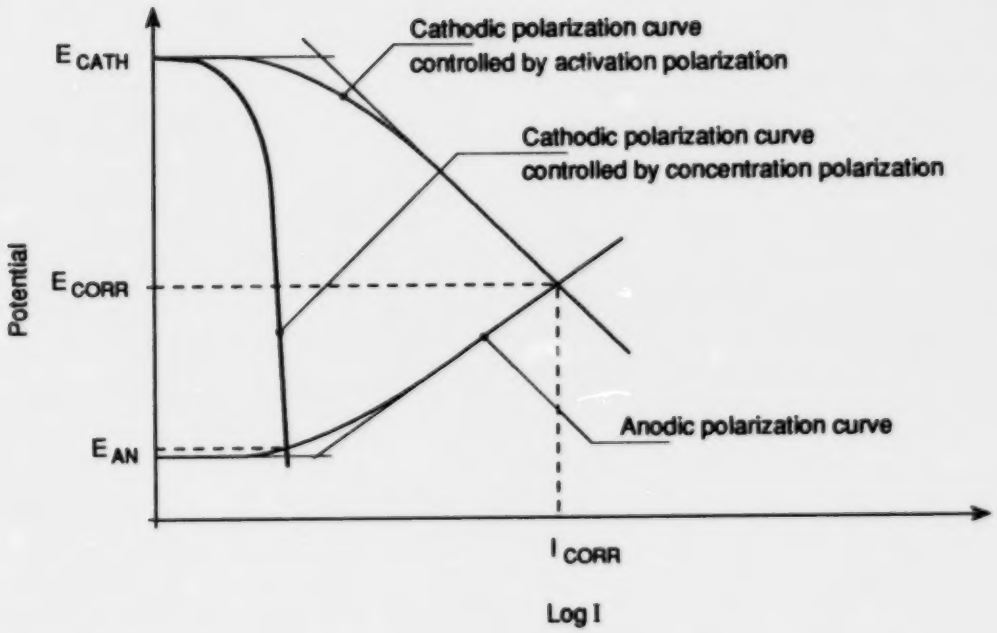


Figure 11/ Polarization Curves